

# COMPARING PERFORMANCE OF SEEDLOT TYPES IN THE KAINGAROA FOREST USING GROUND PLOTS AND AERIAL LIDAR

Comparing the performance of open-pollinated, control pollinated and clonal seedlots in a plantation trial in the Kaingaroa forest utilising airborne LIDAR

Dissertation completed to fulfil requirements for a Bachelor of Forestry Science with honours

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# Abstract

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## Problem:

As more improved planting stock such as clones and genetically improved seedlings are introduced to the market it is important to properly understand the benefits of each production type. Various breeding programmes make claims around performance of their seedlots but there is a shortage of literature around the performance of these production types in a plantation setting for most production species.

## Approach:

One seedling, two cuttings, and 7 clonal varieties were compared in a plantation setting on a single site. The stand was measured via five permanent sample plots (PSPs) per seedlot. The seedlots were categorised by material production type and compared using pair-wise analysis to find statistically significant differences. The seedlots were then compared individually to find any intra-material differences. Available aerial LIDAR was then used to estimate tree height for the total seedlot area and establish whether this was an accurate estimate. Average LIDAR height was then used to estimate tree height for each of the five PSPs to establish whether this would improve the prediction of heights and permit its use for large-scale evaluation of genetic material.

## Results:

Categorising seedlots by material type there was no statistical difference for height performance but there was for DBH and basal area. Clones and open-pollinated seedlots showed superior performance over controlled-pollinated material, but not different from each other. Clones showed reduced height variability over non-clones. DBH and basal area variability was also reduced but the difference was only statistically significant versus open-pollinated seedlots. Comparing seedlots individually there was large variation in performance and variability within material types, with clones showing some superiority and non-clones inconsistent improvements.

The LIDAR tree height model for whole seedlot area showed to be a significant predictor average PSP height but poorly predicted CV. Predicting PSP area provided with LIDAR improved correlations over whole stand predictions for both values.

## Implications:

The performance superiority for clones over other production types in this trial is not as pronounced as previously suspected. Clones do, however, provide a more uniform crop. The LIDAR tree height model could be used for further analysis but not for height variability without further improvement. Result validity was, however, reduced by the lack of trial replication and randomisation. This is the key limitation and makes guaranteeing improvements are due to improved genetics (not environment) problematic.

Key words: *Pinus radiata*, seedlot comparison, open pollinated, control pollinated, clone, LIDAR, estimating tree height, Bay of Plenty, Kaingaroa.

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## 1. Introduction

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New Zealand is renowned for its world class and innovative forestry industry. With almost all of the 1.75-million-hectare plantation forest estate being exotic it comes to no surprise that the vast majority is *Pinus radiata* D. Don (NZFOA, 2014). *P. radiata* accounts for 96% of the North Island plantation estate and 76% in the South Island.

*P. radiata* is of relatively low wood quality and stem form quality compared to many other common timber species. As a result attempts have been made over the years to improve properties such as wood stiffness, along with increasing growth rates, disease resistance and decreased variability. Varying forms of genetic improvement have been used to create the improved planting stock seen today. Clones and controlled-pollinated seedlots are two of the improved stock choices which will supposedly show superior performance in these traits. However these options are often considerably more expensive to produce than the alternative of open pollinated seedlot and GF19 seedlot.

Timberlands Ltd. is a management company based out of Rotorua, New Zealand, responsible for the management of the estate predominantly belonging to Kaingaroa Timberlands Ltd. The area managed by Timberlands Ltd. totals to 189,000 hectares, making it the second largest forest management company in New Zealand. The Kaingaroa estate consists of predominantly *Pinus radiata* with the remainder other minor species such as Douglas fir and *Eucalyptus* spp. Timberlands Ltd. are constantly aiming to improve their resource and as such are interested in the potential benefits improved tree genetics can offer their company. This along with their commercial link with Forest Genetics Ltd. (a forest genetics company on the forefront of *P. radiata* development in New Zealand), has led them to investigate the potential gains from improved forest genetics, including the establishment of a number of extensive clone trials and establishment trials to evaluate potential benefits in a commercial setting.

There is abundant forest genetics literature on how to improve genetic gains and performance. There does, however, appear to be a gap in the literature with regards to comparing plantation trials for various open, controlled and clonal seedlots in a plantation setting other than the single-tree-plot trials conducted by many tree improvement companies. It is important for forest owners and forest managers to understand the

differences and advantages of these seedlot production techniques to allow them to make more informed decisions relating to establishment.

This report will compare a number of open- and controlled-pollinated seedlots and clonal seedlots in a plantation trial setting through the comparison of a selection of planting stock in the Kaingaroa forest. The performance and variability of height, diameter and basal area will be assessed using large-scale genetic material trials and ground plots. The research will then use extensive LIDAR, flown by Timberlands Ltd. as another form of measurement and compare its results of this with ground plots to establish whether this is could be used to further analyse this type of trial.

## 1.2. Background

In 2008 Timberlands Ltd. began deploying a large amount of clonal material into their forest starting off with around 120,000 plants and expanding to 1.5 million by 2015. Clones in the estate have had mixed success, however, results from a number of internal and external trials have prompted some optimism around the potential performance and variability improvements clones could provide their company.

In 2008, coinciding with the beginning of clonal deployment, Timberlands Ltd. established compartment 192, an operational trial of a number of the more promising clonal and non-clonal seedlots from research trials and operational plantings. Diverging from previous clonal trials compartment 192 was set out as an operational trial, intended to be managed accordingly. This provides information and a demonstration on how these seedlots perform in an operational setting while maintaining a level of scientific principle (comparing seedlots on the same site).

## 2. Research Questions & hypotheses

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### Research questions

1. Are clonal, controlled-pollinated and GF19 seed lots indifferent to each other in terms of performance and variability in:
  - Height
  - Diameter
  - Basal area?
2. Are the findings for height and variability consistent between ground assessment and LIDAR?
3. Can LIDAR findings be improved?

### Null hypotheses

1. There is no superiority for controlled-pollinated or clonal seedlots for performance or variability in:
  - Height
  - Diameter
  - Basal area
2. There will be a 1:1 relationship between ground plots and aerial LIDAR
3. LIDAR cannot be improved



### 3. Literature Review

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#### 3.1. History of genetic improvement of *Pinus radiata* in New Zealand

Ib Thulin led early attempts at operational *P. radiata* breeding based out of the Forest Research Institute in Rotorua. Attempts at genetic improvement initially involved the selection of a few plus trees from which seed and grafts were collected, later being used to start clonal orchards and controlled crosses. Quickly the perception changed and moved towards a more extensive programme, using hundreds of plus trees from a much wider geographic range (Burdon, 2008).

By the 1970's New Zealand breeding began to follow a breeding population hierarchy similar to that described in White's conceptual framework (1987). This technique utilises a cycle of steps introducing a larger genetic base, then intensively selecting plus trees for genetic improvement and then multiplying the best material. The genetics programme appreciated that the cyclic approach which viewed tree improvement as an ongoing cumulative process rather than the one-off approach used previously.

Over time breeding objectives have changed considerably. With *P. radiata* widely known for poor form and straightness these were two of the dominant breeding objectives which were also coupled with tree vigour. Early tree breeding made few attempts at improving wood properties despite early research into the heritability of these properties, as increasing the quality of raw materials was perceived as lower risk (Burdon, 1966). This coupled with the reasonable wood properties in old crop stands being harvested around that time (from planting in the 1920s and 30s) and the tree volume/wood quality trade-off, made breeding for wood quality through the 1960s unappealing. The appearance of *Dothistroma* in the 1960s meant breeding resistance to this disease was quickly introduced.

After old-crop was harvested and during a second planting boom in the mid 1960s, it was conceded that forests would need to be harvested at a younger age, as low as 25 years. Wood quality was introduced as an objective to combat the wood property issues associated with these younger age classes, originally using density as a selection criteria for stiffness (Burdon, 2008).

Since these early efforts breeding has changed somewhat. One of the major changes has been a move away from using density as a measure for timber stiffness. It is now realised that traits such as acoustic velocity have a much better relationship with wood stiffness. Moreover, techniques such as vegetative propagation and clonal replication have also been introduced since the original breeding attempts (Sorensson & Shelbourne, 2005).

### 3.2. Rating genetic material (GF plus rating)

The GF plus scheme was implemented in 1998 by the Radiata Pine Breeding Company (RPBC) originally as an objective measure of the growth (G) and form (F) of the many *P. radiata* seedlots developed around the country. The GF rating scheme now uses the Seed Certificate Service (SCS, a separate company set up by the RPBC) to score seedlots based on the performance of its parents in 6 traits, (growth, straightness, branch habit, Dothistroma resistance, wood density and spiral grain in RPBC progeny trials) with the performance of each parent weighted by the proportional contribution of each parent to the seedlot. The traits of their parents are currently rated on a scale of 1 to 30 to provide a final GF rating up to 30 although this is expected to expand as genetics improve over time.

### 3.3. Open-pollinated seed orchards

Seedlot production from an open-pollinated seed orchard is the cheapest production type (Carson, 1986). It has very little control over the crossing of parent plants as both parents are left open to the air, using wind as pollen vector. As a result there is both variability within the two preferred parents (natural genetic variation), and between possible surrounding parent trees. This results in high genetic variability and lower genetic gain compared to other production types. These seedlots are of a low GF rating, generally not exceeding GF19.

### 3.4. Controlled-pollinated seed orchards

Controlled-pollinated seed orchards refer to the control of the crossing and introduction of each parent where the pollen from one tree is introduced to a single cone from another. There is still significant genetic variability due to variability in each parent, but the ability to control which plants to cross improves genetic gain (Carson, 1986)

Cuttings are often used to bulk out otherwise expensive and scarce seeds from controlled-pollinated orchards. These cuttings are a form of vegetative propagation and are generally collected from stool beds in a nursery but can also be collected from the field. The benefits of cuttings can be found in the next section.

### 3.5. Vegetative propagation for *P. radiata*

It is relatively easy to propagate *P. radiata*; as a result this technique has been used widely since the 1960s. Vegetative propagation is a form of cloning which involves the asexual replication of the plant through culturing part of its vegetative structure. Cuttings are one of the most common forms of vegetative propagation. While early attempts at this hoped to capitalise on some of the benefits of pure clonal forestry, many were concerned with maturation or ‘physiological ageing’ of plants (Burdon, 2008).

Cuttings have many uses in stock production; for example cuttings can be taken from trees and grafted onto another root stock in an orchard as a cheap and effective source of seed. Cuttings are also (as mentioned in section 3.4) used to good effect in stool beds. As stool beds are reused over several years the products undergo a process called maturation. While in the first year of a stool bed there are few benefits, from the second year onwards there are improvements (Choosing *radiata* pine tree stocks, 2009) in:

- Stem straightness
- Malformation
- Lighter branching
- Stem taper
- Wind stability
  - Greater root systems
  - Lighter crowns

In practice cuttings are generally found to be hardier due to being physiologically older. As a result cuttings are often planted in areas which are more susceptible to frost, particularly those out of season, during mid spring flush. Much of this ruggedness is also down to more robust planting stock specifications such as a larger root collar and sturdier root system compared to seedlings (D. Witehira, personal communication, October 10<sup>th</sup>, 2016)

### 3.6. Clonal propagation

True clonal propagation in seedlot replication utilises the mass reproduction of a small number of intensively selected clones (Burdon, 2008). There is a range of recognised benefits associated with the use of clones in breeding programs and plantation forestry. Many of the most accepted benefits of clones are discussed in by Carson (1989):

- Conserving superiority from candidate clones without genetic change.
- Easily reproducing clones without genetic gain dilution.
- Effective gamete selection.
- Elimination of pollen contaminations during crossing.
- Enable selection of clones with ‘poor flowering’ so energy is reallocated to growth.

Many other benefits were also identified, however these were either not entirely relevant, or were discredited by Carson (Carson, 1986).

Breeders put clones through a variety of tests before they will deploy them commercially, this both helps to improve their genetics and ensures that they are only deploying the best clones to the market (Aimers & Burdon, 2003). Carson describes a three-step seedlot validation programme used by Forest Genetics Ltd. for testing, selection and validation (M. Carson, S. Carson & Te Riini, 2015):

- Single-tree plots – To identify plus trees to develop further.
- Row-plot validation trials – Many rows of each clone are planted to validate the findings in the single tree plot trials.
- Operational plots – Larger areas of seedlots are planted to gain an understanding of performance across sites on a scale closer to production (similar to the trials used in this report).

There are also risks and/or perceptions about the use of clones in forestry, which have led to a cautious approach from many foresters. The use of clones rather than families removes genetic diversity, potentially leaving a stand open to widespread effects from biotic or abiotic sources (Johnson, 1988). Proper breeding for known threats can help reduce this risk. As suggested earlier, *Dothistroma* resistance is a major part of breeding objectives in the NZ breeding programme. This is an example of breeding to reduce these risks.

### 3.7.Planting stock cost

Due to commercial sensitivity around the prices of planting stock and inconsistent production types it is difficult to find reliable prices for each production type from a consistent source.

**Table 1: 1987 prices for *P. radiata* plant stock of various production types (SuperTree Seedlings, 2016)<sup>1</sup>; (M. Parry, personal communication, October 13<sup>th</sup>, 2016)<sup>2</sup>; (Carson, 1983)<sup>3</sup>.**

Plant type	Price (NZ\$/1000 plants)
Open-pollinated GF19 seedlings	290 <sup>1</sup>
Seedlings from open-pollinated stand select seed	315 <sup>2</sup>
Cuttings from control-pollinated seed orchard seedlings	530 <sup>2</sup>
Micropropagated plants from embryo culture and mass culture of cotyledon tissue (clones)	500-700 <sup>3</sup>

Between SuperTree Seedlings, Rangiora Nursery and Carson (2016) there is a clear variation in price with plant cost per 1000 plants increasing significantly between GF19, cuttings and clones. Bear in mind clone prices are indicative only due the age of the reference.

### 3.8. Juvenile mature-relationships

Due to the long life-cycle of most tree species and the need for rapid and genetic improvement it is rarely feasible to grow trials until harvest age or maturity before making inferences on the performance of individuals within them. Little is known about the relationships between traits such as growth rate, modulus of elasticity and variability in mid-rotation trials versus harvest age/maturity, however, some accounts offer an insight into some of the trends. Libby & Ahuja (1993) suggests that individuals with superior height at mid rotation will generally have increased diameter at harvest age.

### 3.9. Similar Previous Research

During literature review several documents were found containing similar research. While the approach was much different, the overall aim was very similar.

#### 3.9.1. Farmery (2015)

A dissertation completed by previous University of Canterbury student Acacia Farmery looked into the performance of *P. radiata* clones in Panpac forests around Hastings, New Zealand. Her research compared plantation stands of clonal stock with stands with similar full stands of control pollinated stock across five sites/forests at age 4.5 and 7.5. It compared diameter, height, and modulus of elasticity and the variability of these traits. While it is not clear which clones or control pollinated seedlots were used, the clones were also developed by Forest Genetics Ltd. around the same time in a similar geographic area.

In her results Farmery had several key findings. Four clones performed well across ages 4.5 and 7.5 while one did not perform well in the age 4.5 plot. Clones were significantly less variable for diameter at breast height, but not for modulus of elasticity. It also identified that differences in height of clones versus control pollinated seedlots were significant, but not all were. Performance in the stand was very similar to the suggested performance from Forest Genetics Ltd.

#### 3.9.2. M. Carson, S. Carson (2016)

In 2016 Forest Genetics Ltd. (clonal developer and producer of clones for this report) presented findings from a number of genetic trials in the Kaingaroa forest comparing the performance of three forest genetics varieties and control pollinated seedlots to open pollinated GF19 seedlings in a trial setting. The trials reported a volume increase of 15 to 38% for clones compared to the open pollinated seedlots, while control pollinated seedlots had 1% less volume. Similarly the three clones had increased stiffness (5.7 versus 7.9-8.1 Gpa) and density (324 versus 345-373kg3m<sup>3</sup>). A similar trial also in the Kaingaroa forest showed similar results but also showed increased proportion of acceptable stems and *Dothistroma* resistance.

The presentation also mentioned the addition of wood density to the breeding goal, to capitalise on increasing carbon prices which can provide additional non timber revenues as a result of increased carbon sequestration.

### 3.9.3. R. Vergara et al. 2011

Much of the knowledge around variability and performance gains stems research on other similar pine species outside of New Zealand. Vergara, White, Huber, Shiver, and Rockwood compared realised gain from first generation breeding populations of slash pine (*Pinus elliottii* Engelm. var. *elliottii*) in large field trials in south-eastern United States. Along with moderate gains in rust resistance and site index their research found a 7.7% increase in individual tree volume and 10.2% increase in stand yield which is less than the expected gain for these seedlots. Further analysis also suggested that these gains were not consistent across all sites. Interestingly, results were largely consistent across the range of assessed age ranges, from age 5 to 18.

## 3.10. LIDAR

LIDAR (light detection and ranging) is a form of remote imagery which uses high density laser point clouds to create 3 dimensional images of an object (such as trees in a forest). There are several ways LIDAR can be collected which govern its usefulness and limitations. Two of the more common forms of LIDAR are ground-based and aerial. Ground-based LIDAR creates a quality image of 3 dimensional tree stems allowing the user to draw data about tree diameter, form, and branching and tree height. Aerial LIDAR is generally flown by plane and has the added advantage of easily covering larger areas substantially cheaper than ground-based LIDAR; as a result this is a common form of LIDAR amongst plantation foresters. Aerial LIDAR does, however, have its disadvantages. As it is collected from a substantial distance, above an often dense canopy, its accuracy can be limited resulting in less functionality than the ground based variant. Nevertheless aerial LIDAR is a valuable tool in the plantation forestry industry as it allows the user to easily collect population data remotely across a large area rather than plot sampling only a small proportion of the area. It has several uses including tree species identification, stocking, developing digital terrain model and tree height.

LIDAR height is calculated by creating a digital terrain model with the lowest points and subtracting that from the highest points in the cloud to make a tree height model (Hussin & Kloosterman, 2016). A LIDAR based tree height model is not completely accurate due to a number of factors. In a trial Andersen, Reutebuch & McGaughey (2006) found that LIDAR on average under predicted tree height by 1.12m with a standard deviation of 0.56m.

## 4. Approach

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### 4.1. Trial site

#### 4.1.1. Trial Layout

In 2008 Timberlands Ltd. established a plantation scale trial comparing 10 seedlots comprised of:

- 1 open pollinated seedlot
- 2 control pollinated seedlots
- 6 Clones
- 1 mixed clone (mixture of all other clones)

Each seedlot is in continuous areas with no replications. Each seedlot contains 5 0.06 hectare circular permanent sample (PSP) plots randomly located throughout the stand. Ground plots were sampled by InterPine Ltd. in accordance with standard Timberlands plotting techniques using a diameter tape to measure tree diameter at breast height and a Vertex to measure tree height.

The trial is located on the western edge of southern Kaingaroa forest approximately 15 kilometres south of state highway 38, adjacent to the southern tip of Goudies road. Seedlot areas are of varying sizes ranging from 0.81 hectares to 31.64 hectares as noted in table 2, however, in the case of the two control pollinated seedlots, only a portion of the total planted area is technically considered part of the trial (shown in brackets in table 2).

**Table 2: Overview of included seedlots, areas and material source. Note: \* = actual trial area.**

Seedlot	Note	Planted area (hectares)
99/185	OP (open pollinated) GF19 seedling	0.78
02/313	CP 1 (control pollinated) cutting	31.64 (12.57*)
04/503	CP 2 (control pollinated) cutting	22.06 (7.99*)
Clone 15	Forest Genetics clone	5.22
Clone 17	Forest Genetics clone	0.82
Clone 19	Forest Genetics clone	10.95
Clone 30	Forest Genetics clone	3.93
Clone 37	Forest Genetics clone	1.98
Clone 39	Forest Genetics clone	0.98
Mixed clones	Mix of forest genetics clones	3.69

As the trial is intended to be representative of a typical plantation stand, it has been managed with standard silvicultural regime. As such the stand has been subject to a variety of silvicultural practices throughout its life. These can be seen in table 3.

**Table 3: overview of silvicultural regime applied to the trial including timing and comments.**

Operation	Year	Plant age	Comment
Mechanical site prep	2008		Target 1000sph
Planting	2008	0	940 sph (actual)
Release spraying	2009, 2011	1, 3	Orion Glyphosate, Mustang, Silmaxx
Dothistroma spray	2012	5	
Pruning	2013	5	Not GF19, 388sph, 3m target
Thinning	2013	5	793sph
Pruning	2015	7	378sph, 5.6m target lift

In 2013 the entire Timberlands estate was flown with aerial LIDAR, including the area within this trial. As a result this data is available for use in this analysis. The LIDAR itself was flown at 8 pulses/m<sup>2</sup> and the resulting canopy height model and tree height model has a pixel resolution of 1m.

#### 4.1.2. Soil and Site Characteristics

Soil and site characteristics are useful for future between-site comparisons or trial replication.

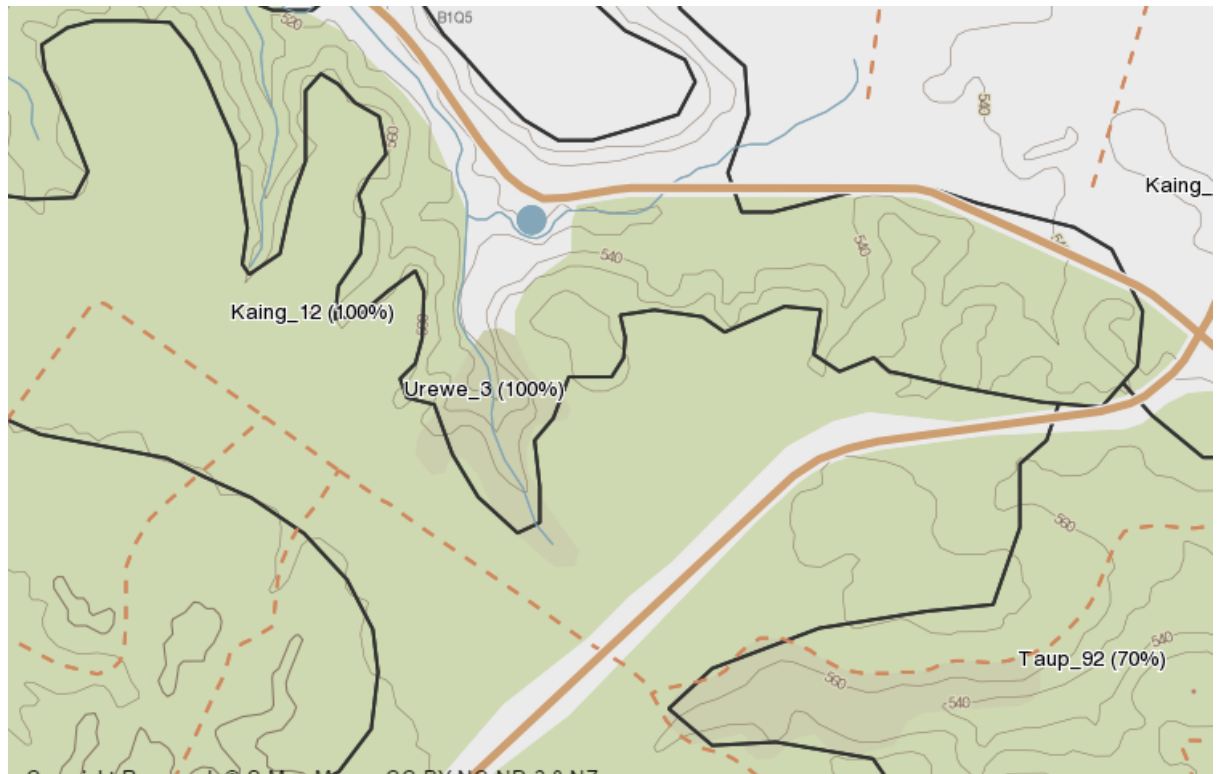
**Table 4: Information about the geospatial location of the trial.**

Altitude (m)	Easting	Northing
649	176°28'11.50" S	38°32'05.74" E

Altitude and GPS location of a central point within the trial sourced from google earth

Using S-map online data from the Landcare Research online database downloaded through the LRIS data portal a variety of information about the soil was compiled.





**Figure 1: Map of distribution of soil types across trial area (LINZ, 2016)**

The resolution and accuracy of the soil data is questionable but soil properties are characterised by the two soil types in the vicinity. The majority of the area (predominantly the flats) is Kaingaroa sibling 12. Descending downhill, the area transitions into Urewera sibling 3. A description of the properties of each of these soil types can be seen in table 5.

**Table 5: Summary of soil properties corresponding with figure 1 (LINZ, 2016).**

<i>Property</i>	<b>Kaingaroa 13</b>	<b>Urewera 3</b>
<i>Drainage</i>	Well drained	Well drained
<i>Soil depth</i>	Shallow (20 – 45cm)	Deep (>100cm)
<i>Soil moisture</i> (PAW)	Moderate to low (60 – 89mm)	High (150 – 249mm)

PAW = weighted profile available water

## 4.2. Analytical Method

### 4.2.1. Trial analysis

Data collected in the field (as outlined in 4.1.1) was loaded into the R Statistical System. The key metrics used in this analysis; height and diameter were extracted, with average diameter used to establish average basal area per tree using the formula:

$$\text{Basal area} = \pi * \frac{DBH^2}{4}$$

**Equation 1: Basal area equation.**

These values were then aggregated to plot level finding the plot mean for height and diameter and summing basal area multiplying to a per hectare level. Building on this the variability was then calculated for each seedlot plot using R, with this then being used to calculate the coefficient of variation (CV) using the equation:

$$CoV = \frac{\theta}{x}$$

$\theta$  = standard deviation

$x$  = sample mean

**Equation 2: Calculating coefficient of variation.**

To develop an understanding of basic trends the plot averages/sums for the three variables were plotted using the ggplot2 package. Seedlots were colour coded based on their respective seedlot types.

Using the TukeyHSD (Tukey's honest significant difference) function in R, a family-wise assessment was conducted using the differences in means between two variables in a given level to create an interval (based on a Studentized range statistic). If zero (or no difference) lays between these values there is no statistical difference. This range is also expressed as an adjusted p-value which was also utilised to show a difference in seedlots. The p-value was used to reject the null hypothesis that there was a difference using a critical p-value of 0.05 (for a 95% confidence level).

Analysis then moved on to comparing the results of ground based plots to those collected by aerial LIDAR. A linear regression was created using equation 3 to predict average plot height using average LIDAR height. The process for finding LIDAR values can be found in 4.2.2. The linear regression used the equation:

$$\text{Height} = \text{LIDAR height} + \text{seedlot} + \text{plot} + \text{intercept}$$

**Equation 3: Linear model used to correct LIDAR data with plot data.**

The linear regression process was then repeated with the secondary LIDAR (height by plot) measurements.

Following the formation of the various linear models residual analysis was then used to check for violations of the various linear model assumptions. Residual vs fitted, normal Q-Q scale location and residual vs leverage graphs were used to test for; heteroscedasticity, non-normality and observations with excessive influence.

#### 4.2.2. LIDAR modelling

Aerial LIDAR was loaded into ARCGIS and converted into a digital terrain model (DTM) and a canopy height model (CHM). The DTM was subtracted from the CHM to provide tree height (THM). As the tree height model retains area with no canopy as a zero (or near zero) area below a given value are set as null values to prevent them from skewing results. Heights below 2m were set to null the set null function in the raster calculator. This null value reflects the pruned height of 3 metres prior to the LIDAR being flown to remove ground points without logically removing tree canopy. The new tree height model (with ground values set as null) was then processed using the tool 'zonal statistics as table'. This tool creates a variety of standard outputs from the raster input differentiated by the input shape files (in this case seedlot boundaries). A linear regression is used to estimate the actual plot heights at age 8 based on average height from the outputs above. The results of this regression provide a correction factor in the form of an intercept. This correction factor can be used to calibrate the LIDAR findings to better correlate with ground plots.

Buffers were then used in ArcMap around the ground plot locations located with a hand held GPS unit during plotting. These plots replicate the plot area used in ground plots. Geometry is again calculated using zonal statistics as table, but this time by plot. Another regression was created to estimate measured plot height based on the LIDAR estimate.

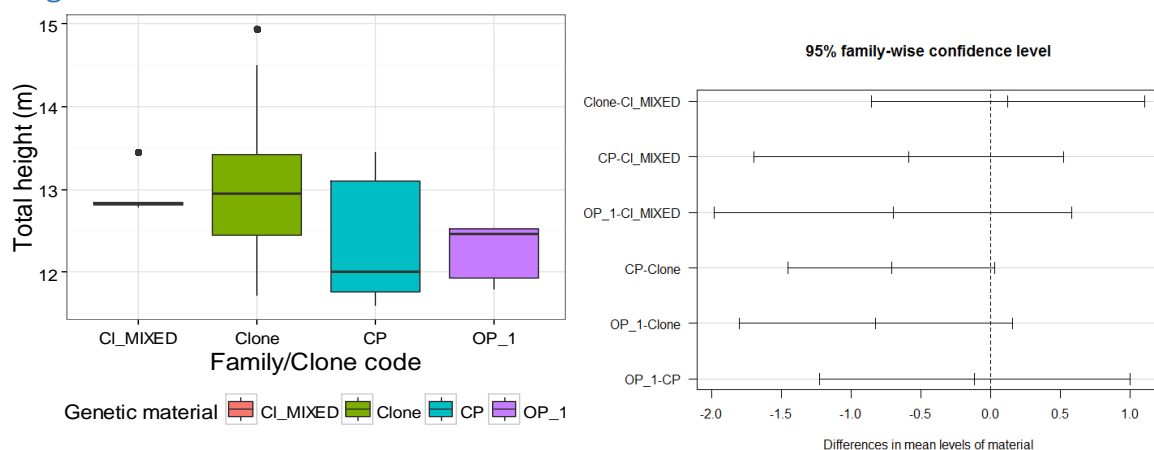
## 5. Results

### 5.1. Plot analysis

#### 5.1.1. Performance

##### 5.1.1.1. By propagation type

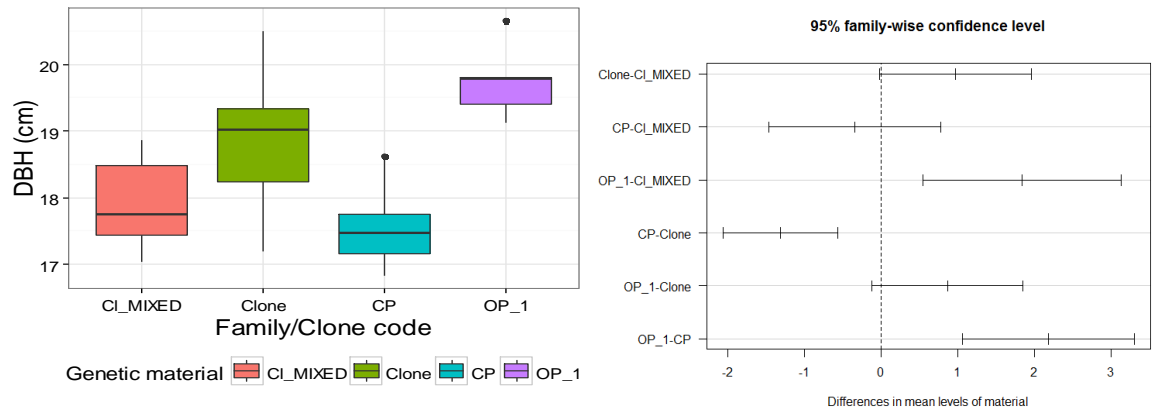
#### Height



**Figure 2: Box plot and pair wise Tukey confidence intervals for average plot height by material type.**

The bar graph initially suggests there may be some difference in the averages of the different material propagation types with mixed and non-mixed clones having average DBH of 12.94m and 13.07m respectively versus 12.35m and 12.24m for control pollinated and open pollinated seedlots. The 95% confidence interval contradicts this with none of the four material type paired comparisons showing any significant differences in tree height. That said, it still suggests that the differences between clones and control pollinated and open pollinated seedlots are larger than the difference between open-pollinated and controlled-pollinated.

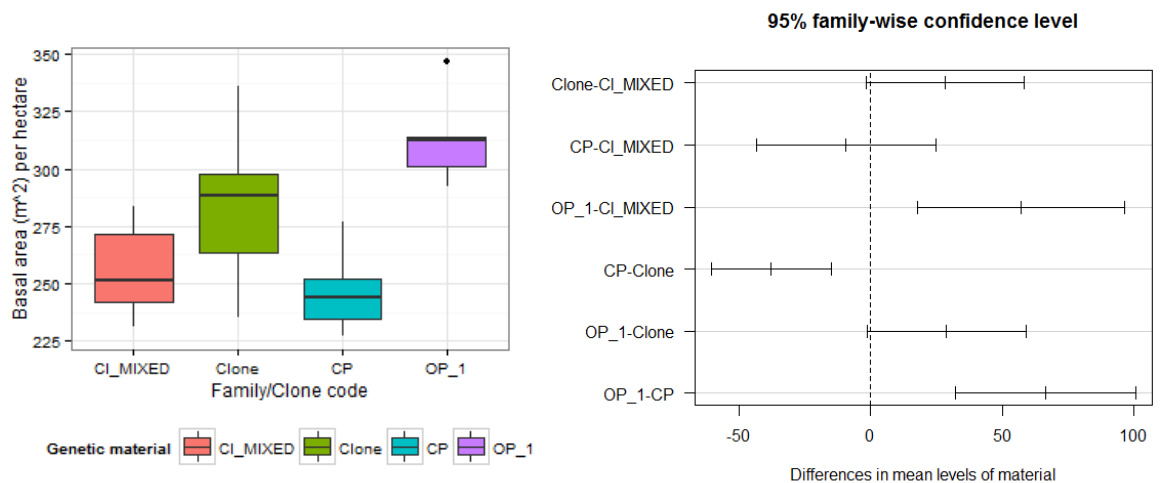
## DBH



**Figure 3: Box plot and pair wise Tukey confidence intervals for average plot DBH by material type.**

Clones and open-pollinated seedlots appear in the box plot to have a higher average DBH with averages of 18.88cm and 19.79cm respectively compared to 17.91cm and 17.57cm for mixed clones and control pollinated clones respectively. The confidence intervals indicate that the open pollinated seedlot has significantly larger DBH than both mixed and controlled-pollinated seedlots and a near significant improvement on average clone DBH. Individual clones have a significantly larger DBH than controlled-pollinated seedlots, however, the difference between clones and mixed clones is not quite significant, with an adjusted p-value of 0.056. Clones and open-pollinated seedlots were not significantly different from each other.

## Basal area



**Figure 4: Box plot and pair wise Tukey confidence intervals for average plot basal area by material type.**

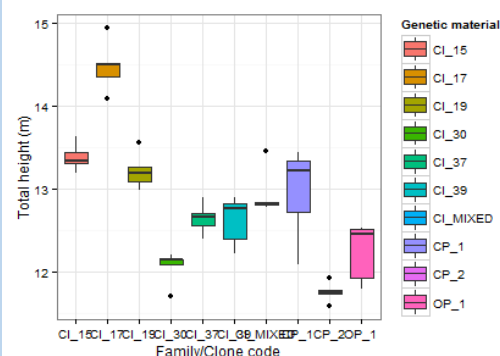
Basal area shows a very similar trend to DBH with open-pollinated seedlots and clones having a higher average basal area than controlled-pollinated but only open-pollinated being higher than

mixed clones. The significance of differences (both those that were and were not significant) was reduced slightly.

#### 5.1.1.1. By seedlot

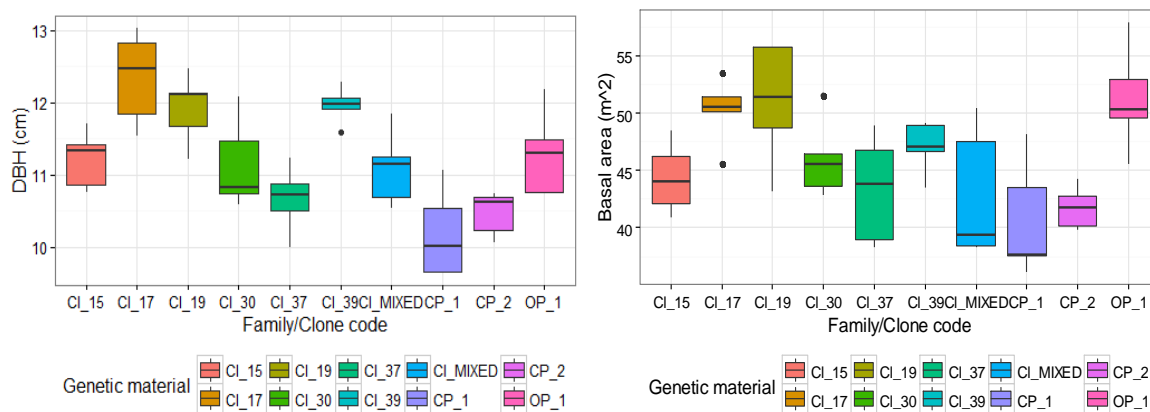
**Table 6: Significance of pair-wise comparisons for height by seedlot using Tukey test. A value of 1 represents being significantly different at 95% confidence**

	Clone						Cutting		Seedling
Seedlot	17	19	30	37	39	MIX	1	2	1
15	1	0	1	1	1	0	0	1	1
17		1	1	1	1	1	1	1	1
19			1	0	0	0	0	1	1
30				0	0	1	1	0	0
37					0	0	0	1	0
39						0	0	1	0
MIXED							0	1	1
CP_1								1	1
CP_2									0



**Figure 5: Box plot of average plot height by seedlot.**

When compared by seedlot rather than propagation type the results of comparisons are somewhat different for height. Material-wise comparisons suggested there was little difference between propagation types, the boxplot and confidence intervals suggest otherwise. While most clones and non-clones are indifferent, 3 clones stand out. Clone 17 is the top performer and has significantly higher average height than any other seedlot. Clones 15 and 19 are also performing well with both having superior performance over most other seedlots. One of the controlled-pollinated and the open pollinated seedlots are performing relatively poorly while the other controlled-pollinated seedlot is competitive with the majority of the clones (only significantly smaller than clone 17). As the two controlled-pollinated seedlots are significantly and drastically different it is likely that the average (used when comparing by material type) has been swayed as a result of combining two such different seedlots.



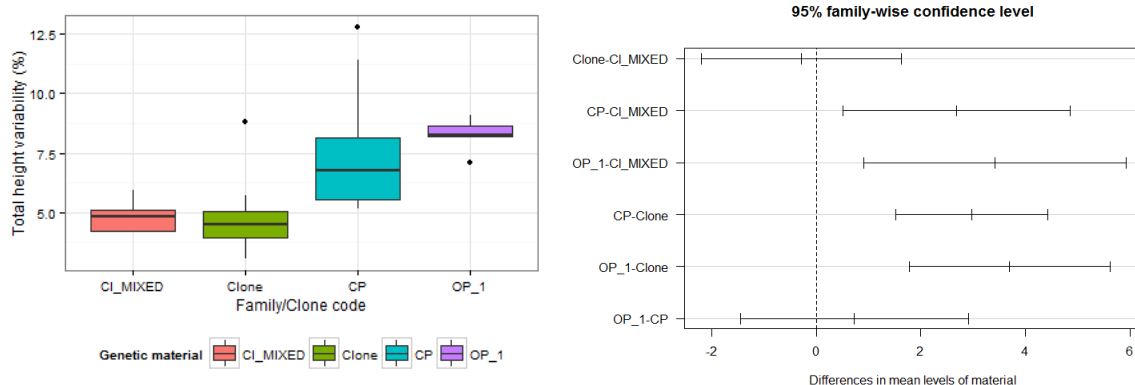
**Figure 6: Boxplots of average plot height and basal area by seedlot.**

The variation of seedlot-wise comparisons versus material-wise comparisons for DBH and basal area is not as severe. The clone superiority shown in the material-wise comparison is also reflected in the seedlot-wise comparisons. However, once more, there is a dominance by a selection of well performing clones (17 and 19) amongst otherwise mediocre clones (non-significant). The perceived dominance in figure 3 and 4 (material-wise DBH and basal area comparisons) by open-pollinated seedlot is now insignificant and appears to be the result of a single well performing seedlot versus an averaged set of superior and poor clones. Nevertheless the open-pollinated seedlot is amongst the best performers.

## 5.2.1. Coefficient of variation

### 5.2.1.1. By production type

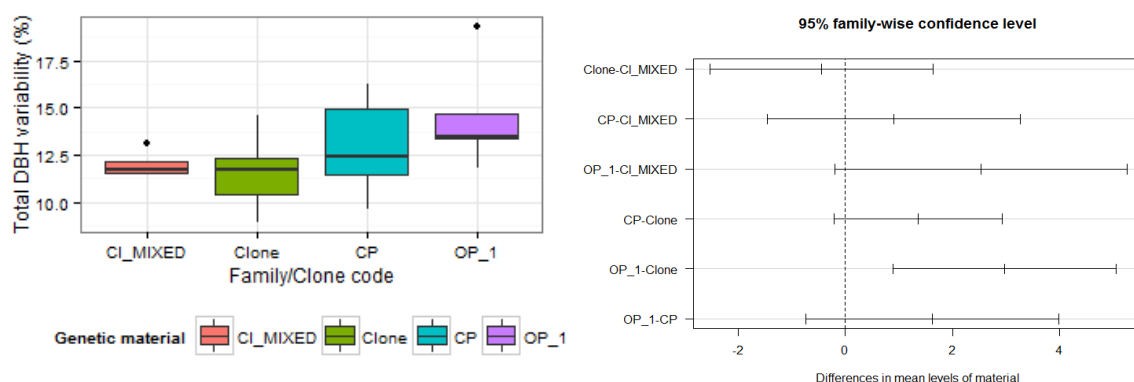
#### Height



**Figure 7: Box plot and pair wise Tukey confidence intervals for average plot tree height variability by material type.**

The box plot suggests that both the clones and mixed clones have a lower average CV than both non-clone seedlot types with average CV moving from left to right of 4.84%, 4.56%, 7.52% and 8.25%. The confidence interval supports this claim with both clones and mixed clones having significantly lower coefficient of variation at 95% confidence. Neither the two clonal nor two non-clonal seedlots were different from each other.

## DBH

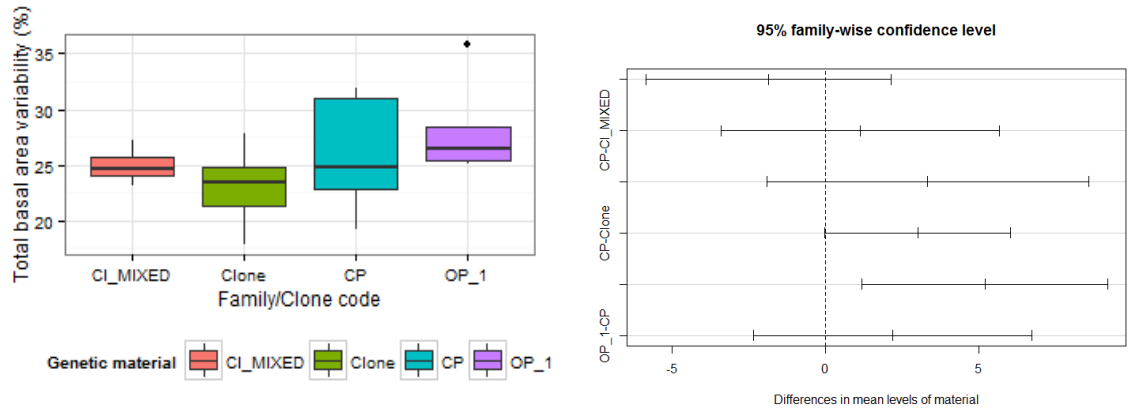


**Figure 8: Box plot and pair wise Tukey confidence intervals for average plot DBH variability by material type.**

The differences between material types are not as apparent for average CV for DBH according to the box plot, however, the average plot variability suggests more variability for open-pollinated seedlots with 14.54% versus the others with none exceeding an average of 12.92%. Looking at the confidence intervals clones have a significantly lower coefficient of variation for DBH than open pollinated seedlots at a 95% confidence limit. Looking at the adjusted p-value (found in appendix table 4) mixed clones would also have significantly lower CV than OP seedlots should 90% confidence be accepted.



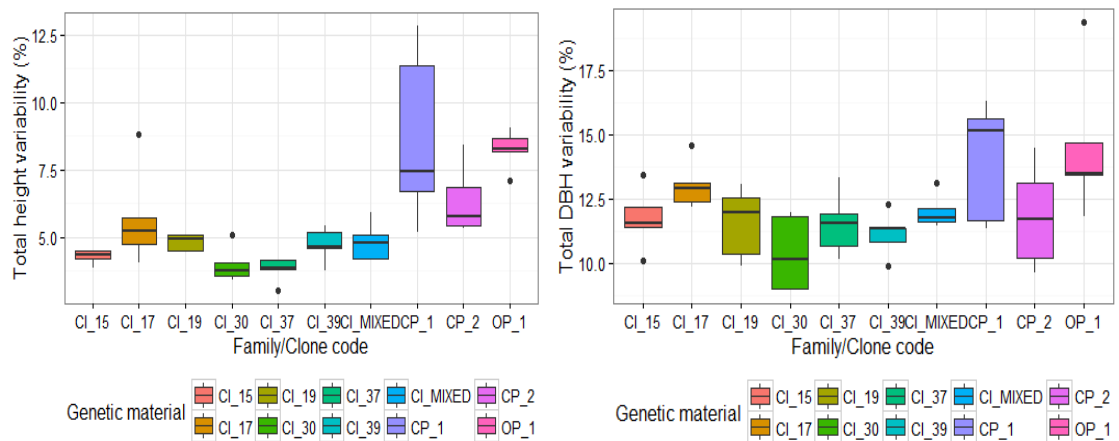
## Basal area



**Figure 9: Box plot and pair wise Tukey confidence intervals for average plot basal area variability by material type.**

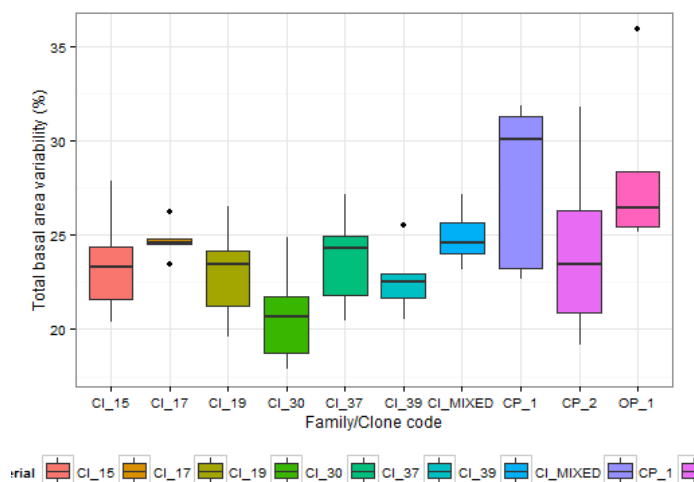
The trends for basal area are again similar to DBH. The relative trends for the material types are very similar, albeit much higher. However, the confidence intervals suggest that the differences between clones and controlled-pollinated seedlots are now more marked although still not reaching significance at 95% confidence, but with an adjusted p-value of 0.052 it is very close.

### 5.2.1.2. By seedlot



**Figure 10: Boxplots of average plot height variability and DBH variability area by seedlot.**

Controlled-pollinated seedlot one and the open-pollinated seedlot have the highest average coefficient of variation across both height and DBH variability, significantly higher than all clones (excluding clone 17 due to its single highly variable plot). Clone 17 has the highest average CV for height of the clones, but this difference is not statistically significant. This general trend is continued for DBH and basal area, although, the differences are not as substantial. These seedlot-wise trends are consistent with the findings of material wise comparison earlier (figure 7 and 8). Across all three variables there is again a tendency for superiority (reduced variability) from clonal seedlots over non-clonal. Again the stark difference between the two controlled-pollinated seedlots (one being competitive with clones and one being poor) for DBH but especially height, appear to have cancelled each other out as opposed to a range of relatively consistent clones.



**Figure 11: Box plot of average plot basal area by seedlot.**

Similarly to diameter there is again a general superiority for clones over other material. Interestingly the open pollinated seedlot and controlled-pollinated seedlot one have the highest average CV's of 28.25% and 27.82% respectively. These are compared to an overall average CV for basal area of 24.37%.

### 5.3. LIDAR

**Table 7: Average tree height from directly collecting seedlot area with LIDAR.**

Seedlot	Height (m)
02/313	4.60
04/503	4.48
99/185	4.73
FGC/15	5.49
FGC/17	5.62
FGC/19	5.17
FGC/30	4.81
FGC/37	5.03
FGC/39	4.96
Mixed	5.13

Using LIDAR to find the average height for each seedlot area resulted in a drastically different result for all seedlots than found previously for both average tree height and CV.

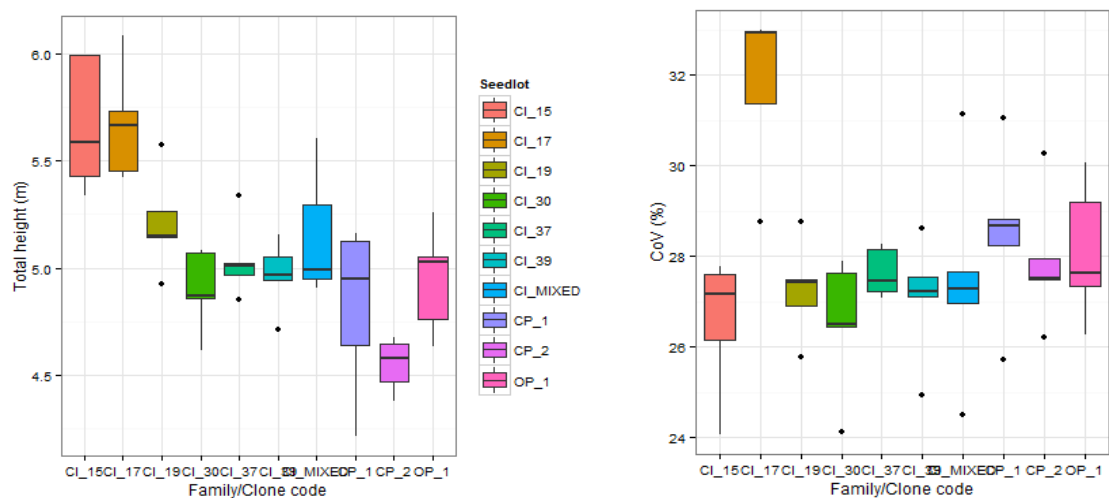
**Table 8: Summary of significance of linear regression components and R squared. Key for significance levels.**

		whole area height	Whole area CV	Plot delineation height	Plot delineation CV	Code	Significance level (%)
	Intercept	***	***	***		***	99.9
	LIDAR height	***	***	***	*	**	99
Clone	17	***	***	***		*	95
	19	-	***	*		-	90
	30		***	***			
	37		***				
	39		***				
	Mixed						
Non-clone	CP 1	***	***	**	***		
	CP 2		***	**	*		
	OP 1			**	***		
	Adj R squared	88.74%	57.27%	95.83%	60.37%		
	R squared	88.65%	65.12%	96.68%	68.46%		
	Residual standard error	0.2951	1.336	0.1606	1.287		

The LIDAR Tree-height model for the entire seedlot area in table 8 is shown to be a significant predictor of average height in the plots with both the variable and the intercept of the model being significant. The adjusted  $R^2$  for the overall model is relatively. An  $R^2$  of 88.74% is generally

considered good (especially considering there are so few dependant variables) but it means a large proportion of total variability is left unexplained. That is to say the model should be improved before being used. The model also shows very little variation of seedlots from the mean, which is not what would be expected reflecting on the findings from plot seedlot comparisons. It is likely that this is a result of low LIDAR output resolution, with a single height value being computed for an entire seedlot area (often many hectares) being used to predict 5 PSP plots within that area.

Coefficient of variation for the area shows an even poorer fit. This model only shows an adjusted R square of 57.27%. However, the model does suggest that both the intercept and LIDAR height are a significant predictor.



**Figure 12: Total height and CV of plot locations as predicted by LIDAR by plot location and seedlot.**

Calculating tree height using LIDAR for each of the seedlots there are some clear differences between the seedlots compared to the plot findings. Bear in mind these are based on LIDAR flown earlier than the plots but, overall the general trends appear consistent. Worth noting is that the magnitude of particularly CV is drastically different with variability calculated from plots ranging from 3.04 to 12.8 % while variation calculated from LIDAR ranges from 24 to 33%.

By calculating height for only the estimated ground plot areas the accuracy was increased. The model now has an adjusted R square of 95.84%. Under this model only clones 37, 39 and mixed clones are not significantly different from the mean. A trend which may be expected looking at figure 2 where these three seedlots are around the average height.

**Table 9: Coefficients and intercepts for linear models based on whole seedlot and plot based models**

			whole plot height model	Whole plot CV model	Plot based height model	Plot based CV model
		Intercept	5.216	107.230	7.805	-2.664
		Height coeff	1.498	-3.544	0.984	0.262
Seedlot Coefficient	Clone	17	0.902	7.738	1.090	0.054
		19	0.321	-4.542	0.282	0.338
		30	-0.301	-7.172	-0.569	-0.288
		37	-0.036	-4.582	-0.117	-0.755
		39	0.035	-7.113	-0.072	0.293
		Mixed	0.104	-1.286	0.069	0.306
	Non-clone	CP 1	0.912	16.849	0.410	3.901
		CP 2	-0.108	3.981	-0.528	1.719
		OP 1	singularities	singularities	-0.431	3.563

Having calculated coefficient estimates, the model can be used to increase the accuracy of the LIDAR outputs. The model intercept serves as a correction factor for any systematic error in collecting tree height from LIDAR. Using the height coefficient, average plot height is calculated by adding the correlation factor by average height (or coefficient of variation). An additional correction factor is then used to correct the height for each given seedlot. The final equation for plot based equations can be seen below.

$$\text{Plot height} = 0.984x + \text{Seedot coefficient} + 7.805$$

Where  $x$  = Lidar plot height (m)

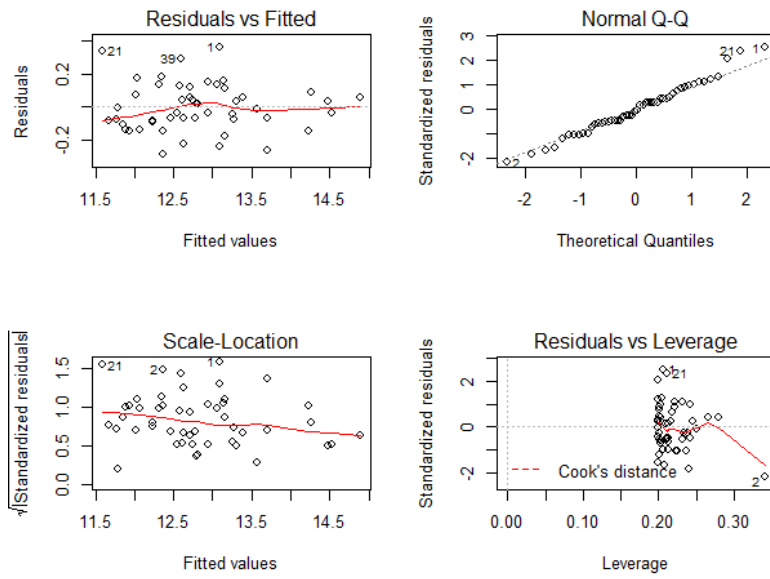
$$\text{Plot CoV} = 0.262x + \text{Seedot coefficient} - 2.664$$

Where  $x$  = Lidar plot CV (%)

#### 5.4. Residual analysis

Before models can be used to make any inferences they must first be checked to ensure they meet the assumptions of a linear model. Using the example of plot based height model the residual analysis suggests that the model does meet the required assumptions.

- The residual vs fitted and scale-location graphs suggests that the data is relatively homogeneous
- The Normal Q-Q graph shows the data is normally distributed
- In the residuals vs leverage graph the value line is not outside of the Cook's distance isolines, suggesting there is no evidence of excess influence by any points.



Analysis of the remaining three linear models show the same result, with none of the graphs suggesting violation of any of the assumptions.

## 6. Discussion

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### 6.2. Seedlot selection

#### Performance

Clones performed better for height, cuttings for diameter and basal area. The difficulty is suggesting which of these values (height or DBH and basal area) to base implications on and whether this superiority will be continued to maturity.

Libby & Ahuja (1993) found that trees which were tall in juvenile trials (similar to these trials) were more likely to have increased diameter and hence higher volume growth towards maturity. This suggests that clones (having superior height growth, particularly for clones 15, 17 and 19) having the potential to be the best performers towards maturity.

#### Variability

While the differences in quantitative variables were marginal (height and DBH), the differences in variability between planting stock are far clearer cut. Clones in the Kaingaroa estate offer a far less variable resource than the other stock types. This alone is of some use to a perspective manager, a less variable stock could provide a more predictable resource at harvest making both marketing and planning for a long range forest yield easier.

Reduced stand variability could also have additional benefits during establishment and silviculture. While it was established that clones were more expensive, the reduced variability could result in less need for intensive thinning of trees, meaning stands could be established at a lower stocking, immediately reducing the significance of the higher establishment costs. The question is whether the potential additional volume growth (at harvest age) is enough to cover the remaining additional cost, bearing in mind that (if using discount cash flow analysis) additional revenue would be discounted 25 to 30 years, while establishment costs would not be discounted at all.

There are however weaknesses to a regime with reduced variability. While less variability means less silviculture is needed, it also means there are few 'stand-out trees' on the higher end of the normal distribution to select during silviculture. In a more variable stand a large proportion of variability can be removed through repeated thinning. This could result in a cuttings stand, with the same pre-thin average volume as a clonal stand, with a higher volume and similar variability post thinning.

### Other properties

In this report much is said about the performance and variability of height, DBH, basal area and variability, but there are a number of additional tree traits, not measured in this trial, which are potentially very important as well. Timber properties are probably the most important additional trait. As discussed earlier *P. radiata* are known for their relatively poor intrinsic wood properties. Over time wood quality has become one of the major objectives traits in many breeding programmes. The impact of improved wood quality can be immense, leading to a larger proportion of higher value structural grade timber. While it is possible that these can be included in the future, neglecting to include a measure of wood quality is an oversight. It is worth remembering though that high wood quality may not always be a key objective. Some regime types such as a stand geared for high production pulp or export saw logs market would not benefit from a seedlots with improved structural wood properties if the producer intends for the wood to be used for pulp or chip anyway.

### 6.3. Validation against similar trials

#### Farmery 2015

In previous research undertaken by Farmery (2015) which was also based in plantation stands, clones were found to have increased height and basal area over control pollinated seedlots. This is contradictory to what is shown in this report. There are some distinct differences between the studies which may have contributed to the difference in findings. In Farmery's study a small number of clones and a single control pollinated seedlot were compared. First, as this is purely a plantation stand (never intended to be used for a trial) these clones were specifically selected to do well for the site and increase economic return. By comparing clones chosen for that site it would be expected that they would perform better. The trial also only compares a small selection of clones (as few as one) with one control pollinated seedlot. One of the key results of this analysis is that there is substantial variation even within material types. By comparing such a range of seedlots in this report (not only top performers) it is expected that there would be less obvious differences between the subjects. On a positive note, both reports did find some clones performed especially well over all sites.

#### Carson 2016

Carson's findings around clonal superiority, also in the Kaingaroa forest, suggested there was a greater difference between various seedlot types than in this report despite having many seedlots in common. This is likely to be as a result of a number of factors. Carson's trials were based on



randomised complete block trials, not on plantation establishments. As a result the trial would not have received the same silvicultural treatment and due to the presence of blocking would have less effect from site variation. This trial also only compared a selection of the top performing seedlots rather than also including a number of additional available seedlots. Analysis for this trial was also restricted to comparing straight averages rather than more sophisticated statistical comparisons such as ANOVA. Given the substantial range between plot averages on many of the variables the difference between seedlots is not significant despite some plots showing signs of superiority.

#### Vergara et al. 2011

While it is hard to comment on similarities between the findings in this report and Vergara et al. (as neither individual volume nor stand volume were assessed in this report, however, Vergara et al. suggested improvements were limited and not necessarily consistent, a finding was largely supported by this report.

### 6.4. Implications and opportunities

These trials are based on a small number of sites, all within the Kaingaroa forest across small spans of geographic and genetic material. As a result, any strong inferences can only realistically be made for areas within the central North Island near the trial sites, similar soil etc.

Timberlands Ltd. have ambitions of large scale clonal establishment in the future. These findings suggest that while there is some merit in the use of clones, the benefits are potentially not as substantial as first thought. Re-evaluating the extensive use of clones in their forest accounting for what appears to be a reduced actual gain may be wise. It is possible that management are aware of the findings and already have plans in place to match the use of clones to regimes which will maximise its advantages and ensure they are using clones which have performed particularly well in other trials. If not, it is possible that they will not receive the gain they had been hoping for.

Libby & Ahuja (1993). suggests that expected returns are far higher for a clearwood regime than for a pulpwood (or high pulpwood output) regime. By utilising clones or controlled-pollinated seedlots it is suggested that yields of pulpwood can be reduced considerably (as much as 70%), replaced by a larger proportion of higher value clearwood and saw logs (Gleed et al. 1991). If genetic improvement is able to increase the proportion of higher value logs, as well as the absolute volume (as suggested in the results for several of the clone seedlots) it is possible that the additional establishment cost may be justified.

### Wider implications

While this report is based largely around deployment in the Kaingaroa forest, broader recommendations can be made to the New Zealand forestry industry and *P. radiata* foresters around the world.

The most important recommendation is to ensure seedlots are chosen properly, not simply relying on the clones to all be superior in all ways. Most clones were superior (compared to other seedlots) for height, but for diameter and basal area clones were not as dominant. A number of clones performed poorly across the board. Improper seedlot selection purely relying on 'improved stock' and inadvertently using these clones would be a poor managerial choice resulting in increased establishment costs potentially without increased harvest yield.

## 6.5. LIDAR

While there are some major differences between the findings from the analysis of plot data and seedlot wide LIDAR data, the significant correlation between the two is a positive result. It is likely that a number of factors will have attributed to this difference including the manner in which the two datasets differ.

### Systematic error

Differences in data collection techniques can also make a substantial difference to plot/LIDAR correlation and overall accuracy. Using LIDAR and its tree height model, height is not calculated based on the single highest point of a tree (like standard plotting techniques). Instead the tree height model uses the area at the top of the crown (including the top). This reduces the average height as it is more of a measure of crown height rather than absolute tree height. Nevertheless, as this is consistent across the seedlots the trends on average height should still be consistent with that of plotted height. With calibration this could be removed, applying an average correction factor would improve accuracy and allow the user to better measure heights of areas within the trial by removing the systematic error and differences in data collection. The presence of a systematic error is characterised by the significant intercept in the model and supported by a knowledge of the systems involved in creating tree height from LIDAR. This impression is reinforced in Gatziolis, Fried & Monleon (2010), where systematic error was also suggested as a leading cause of inaccuracy when calculating tree height using LIDAR. The publication suggested delineation of trees to provide absolute values of tree height for every tree in the stand would be an effective way to remove this systematic error and therefore improve accuracy. This is true and it is likely that this would be effective on this site. Unfortunately, the skillset and software required for this is beyond the scope of this report. A simpler (but possibly less effective) approach is to use the equation created in this report from the LIDAR outputs to correlate them better with the measured value. This can be done

by using the linear model and essentially calculating approximate ground values for a given location with LIDAR outputs. As the error is systematic (so applied to seedlots equally) this may also be effective.

Despite the differences between performance and variability of height between ground plots and LIDAR, it is likely that LIDAR is still an effective way to estimate height and variability. Use of ground plots only captured a relatively small amount of the total area and therefore total variation. Part of the appeal of using a plantation trial is finding trends over an entire stand. Simply using 5 ground plots provides little extra understanding of a seedlot over an establishment trial raising some concern as to whether the ground plots are truly representative of the variation and performance of each seedlot. Using LIDAR to estimate variability and performance across the entire area will provide a far better idea of the true performance. It is likely that a large amount of the difference between the initial LIDAR estimation and plot measurements is actually a valid difference in tree height and that the LIDAR is giving a more representative sample of the trial.

Low is another source of inaccuracy. The resolution of the tree height model used in this analysis of 1m is relatively large (poor resolution). As a pixel value will be based on the average of the LIDAR points within it, the larger the pixel the less representative the pixel will be of the area within it, thus losing accuracy.

#### LIDAR null values problem

Pre-emptive sensitivity analysis showed there was a positive correlation between the maximum tree height set as null values and similarity to LIDAR models. At face value it appears logical that the maximum null value should continue to be increased until the average height best matches average tree height from plot data. Upon further thought this is not the case. As the null value is increased it begins to transition from removing ground points and undergrowth (what the processing is intended for), to removing data from the height model itself.

Due to the way the tree height model is formulated, the model also includes areas of crown well below the peak of the tree, this is not a true measure of tree height, merely canopy height. While these points reduce accuracy and cloud the actual tree height calculation (as would any point other than the peak of the tree), it is not wise to continue removing these points. The main reason for this being it is not possible to ensure the points removed are removed consistently between trees and seedlots (every tree has a different tree height). The difference in tree height would mean for each increase in maximum null height each tree would have a different proportion of its crown removed. The only way to ensure proper consistency and accuracy in this is through tree delineation. This

approach maps out each tree separately. By finding the maximum of each tree, rather than the average across an area a single value is found for each tree, and considerably more values per area. By using LIDAR to measure tree height by tree (rather than by seedlot or even by stand) it can be ensured that only the peak of each tree is measured, rather than the canopy as well. Unfortunately, to automate this process requires a far more sophisticated suite of software than is available and manual delineation is not practical for this area. As a result, a level of inaccuracy must be accepted to ensure the data being collected is unbiased and more reliable.

#### Implications for LIDAR

The analysis suggests that LIDAR and a tree height model can be used to accurately predict plot values. However, it is recommended that a correction factor is used to improve accuracy of the outputs so they better reflect the actual findings on the site. It is also suggested that with this corrected LIDAR be used to compare seedlots in addition to standard ground plots in the future. Timberlands Ltd. is due to re-fly their estate sometime in the near future. This more recent LIDAR should give a better understanding of performance by reducing the time lag between the two data collection times.

#### Temporal data variation

As stated, there is a substantial difference between the date LIDAR was flown and the date ground PSP plots were re-measured. This temporal difference will account for a large proportion of variation between ground measurements and LIDAR data but without more recent LIDAR data for the area it is infeasible to substantiate the level of difference. Timberlands Ltd. have plans to re-fly LIDAR in the estate in the near future. This would be an opportunity to decrease this time difference and increase the model reliability.

## 6.6. Limitations

#### Lack of replication

From a statistical point of view the lack of trial replication is the most significant limitation in this report. While each seedlot in this trial is of a relatively large size and as such incorporates a relative level of site variation, it is impossible to guarantee differences in seedlot performance are due to superior genetics and not simply site variation. Site has a significant effect on plant performance and as such if trees are on a better site with better soil or water properties they will likely perform better (Baltunis, Gapare & Wu, 2010). Attempts were made to ensure no PSP plots were in areas which are too seriously affected by intra-site micro variation but without replication and randomisation of this site variation there is scepticism (or at least hesitancy) about the reliability of the results.

### Single site

Within this trial only a single site was used. This single site limits the validity of inferences for the wider estate (such as recommended seedlot for future establishment). It would be wise to establish similar trials elsewhere in the forest or include results from other establishment trials before acting on any recommendations. These additional trials would also help to differentiate between genetic and environmental effects and provide additional information on how performance of these seedlots will differ across different site conditions.

### Difference in plotting intensity

All seedlots were plotted using the same number of circular plots (5) but not all of the planted area were identical. Trial areas for the various seedlots varied from 0.78 to 12 hectares. As a result, the proportion of the planted area which is plotted will differ considerably. As height analysis using LIDAR captures the height for 100% of the area this could attribute to the differences between not only the difference between average plot height and average LIDAR height, but also the varying success of LIDAR for predicting the height of each seedlot.

This difference in seedlot area is also problematic for inferences with LIDAR analysing entire seedlots variability. Increasing areas will likely result in increased variability (more site = more chance of variation).

### Difference in site

Looking at the tree height model and soil type maps it was clear there was variation across the site, some seedlots more than others. Given the trial design and large scale it is impossible to ensure that the site conditions including soil type, slope and aspect are kept consistent across the trial. While the size of the trial helps to reduce the effect of particularly micro site variation, it is difficult to accurately attribute variation (or differences in variation) to genetics and not simply site. Around the area where clones 17, 19 and 37 were located the soil type and soil depth maps suggest that the soil transitions and with it the soil depth changes from

### Range of genetic material

The genetic material trailed on this site is characteristic of production for Forest Genetics Ltd., both at the time and at present. However, there are countless alternatives throughout various other seed production companies (both within and outside of New Zealand) including a number of other

clones and hybrids. It is possible that this is not a fair representation of the benefits of any of the seedlot types.

#### Alternative important traits

There are a number of additional traits not included in analysis for this trial which may be of extreme importance for a forestry company, particularly intrinsic properties. These include wood density, microfibril angle and Dothistroma resistance. These values were not available for this site but should also be looked into.

#### Extrapolating LIDAR

Regressions only explored the relationships between this set of LIDAR (flown 2013) and the PSPs measured in 2016. While it is possible they may accurately predict other sites of different ages, or different average tree height range (outside of the tree plot height of LIDAR height range) it is advised that further analysis is carried out before relying on the information fully.

#### Use of single LIDAR output

In this report analysis looked at using only average tree height to predict ground plots. While logic suggests this would be the best predictor of PSP height this may not be the case. LIDAR provides many outputs (over 100) including max point, top 25% of points and top 50% of points. It is possible that one of these metrics could be a better predictor of plot height, or if added to the model could help to explain a larger proportion of the variability and result in a more accurate and reliable model. However, given average height is one of the most common metrics and that this report is not intended as a review of LIDAR outputs this will suffice.

#### Long-term trends and extrapolation

While there are signs that clones have superiority it is still worth remembering that these trees were measured at age 8: a long time before harvest. The debate is still out as to whether performance in mid rotation trials are a proper representation of harvest age. As suggested earlier, trees with superior height as juveniles tended to have superior diameter at maturity. However, there is little literature to suggest how trees will continue to develop through to harvest age. Whether trees will retain relative superiority or continue to grow equally and have superiority diminish as a proportion of total performance.

## 7. Conclusion

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On average clones did not perform statistically better than other material types for height performance, but did perform better than controlled-pollinated seedlots for DBH and basal area but were not as good as open-pollinated seedlots for this. Individual clone seedlots did perform much better, particularly for average height. When compared by seedlot type the differences were more severe. Several seedlots performed well above the others, particularly for average height.

Clones had significantly lower height variability than controlled and open-pollinated seedlots with reduced variability for DBH and Basal area. This is accentuated for several seedlots when compared individually with some clones showing exceptional variability but one of the controlled-pollinated seedlots being competitive.

Seedlot area LIDAR height was a significant predictor of plot height but less for height variability. This was able to be improved by predicting only the plot areas with the opportunity to use this correlation as a correction tool. Despite the relatively poor ability to predict variability (particularly) and some variation from plot statistics it was decided it was still a valuable form of seedlot comparison and will likely be a better form of comparison.

## 8. References

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- Aimers-Halliday, J., & Burdon, R. D. (2003). Risk management for clonal forestry with *Pinus radiata*—analysis and review. 2: technical and logistical problems and countermeasures. *New Zealand Journal of Forestry Science*, 33(2), 181-204.
- Andersen, H. E., Reutebuch, S. E., & McGaughey, R. J. (2006). A rigorous assessment of tree height measurements obtained using airborne LIDAR and conventional field methods. *Canadian Journal of Remote Sensing*, 32(5), 355-366.
- Baltunis, B. S., Gapare, W. J., & Wu, H. X. (2010). Genetic parameters and genotype by environment interaction in radiata pine for growth and wood quality traits in Australia. *Silvae Genet*, 59, 113-124.
- Burdon, R. D. (1966). *The improvement of Pinus radiata*. Paper presented at the New Zealand Forest Service, FRI Symposium No. 6.
- Burdon, R. D. (2008). Breeding radiata pine-historical overview. *New Zealand Journal of Forestry*, 52(4), 4.
- Carson, M. J. (1986). Advantages of clonal forestry for *Pinus radiata*—real or imagined. *NZ J For Sci*, 16(3), 403-415.
- Carson, M., Carson, S., & Te Riini, C. (2015). Successful varietal forestry with radiata pine in New Zealand. *New Zeal J Forestry*, 60, 8-11.
- Choosing Radiata Pine Tree Stocks. (2009, September 7). Retrieved October 09, 2016, from <http://www.nzffa.org.nz/farm-forestry-model/resource-centre/farm-forestry-association-leaflet-series/no-2-choosing-radiata-pine-tree-stocks/>
- Eliasson, L. (Ed.). (1977). *Vegetative propagation of forest trees-physiology and practice*. Institute for Forest Improvement.
- Farmery, A. (2015). *The Performance of Blocks of Clones in a Radiata Pine Production Forest*. Christchurch: University of Canterbury, School of Forestry.
- Gatzliolis, D., Fried, J. S., & Monleon, V. S. (2010). Challenges to estimating tree height via LiDAR in closed-canopy forests: a parable from western Oregon. *Forest Science*, 56(2), 139-155.
- Gleed, J. A., Arnold, R. J., & Siegfried, J. (1991). Radiata pulpwood production--an optimum approach via clonal forest plantations. *Appita journal*.



- Hussin, Y. A., & Kloosterman, E. H. (2016). Accuracy of Measuring Tree Height Using Airbourne LIDAR and Terrestrial Lasar Scanner and Its Effects on Estimating Forest Biomass and Carbon Stock in Ayer Hitam Tropical Rain Forest Reserve, Malaysia. Enschede
- Libby, W. J., & Ahuja, M. R. (1993). Clonal forestry. In *Clonal Forestry II* (pp. 1-8). Springer Berlin Heidelberg.
- LINZ (2016). Land Information New Zealand, Retrieved September 5<sup>th</sup> 2016:  
 URL: <https://iris.scinfo.org.nz/layer/478-s-map-soil-depth-september-2016release/?nc=&z=15&c=38.54027781506087%2C176.4664869682617&mt=OpenStreetMap>
- NZFOA. (2014). *2014 Facts and Figures*. Wellington: Ministry of Primary industries.
- Persson, Å. J. U. H., Holmgren, J., Söderman, U., & Olsson, H. (2004). Tree species classification of individual trees in Sweden by combining high resolution laser data with high resolution near-infrared digital images. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(8), 204-207.
- RPBC. (2002). *Rating the Genetic Quality of Radiata Pine*. Rotorua: Radiata Pine Breeding Company.
- Sorensson, C.T. and Shelbourne, C.J.A. 2005. Clonal forestry. Pp. 92-96 in: *Forestry Handbook*, 4th Edition,
- Sweet, G. B. (1973). *The effect of maturation on the growth and form of vegetative propagules of radiata pine*. New Zealand Forest Service.
- White, T. L. (1987). A conceptual framework for tree improvement programs. *New Forests*, 1(4), 325-342.
- Zhao, W. (1999). Growth and yield modelling of *Pinus radiata* in Canterbury, New Zealand.

## 9. Appendix

**Appendix Table 1: Significance of pair-wise comparisons for DBH performance by seedlot using Tukey test. A value of 1 represents being significantly different at 95% confidence**

	Clone						Control-pollinated		Open-pollinated
	17	19	30	37	39	Mixed	1	2	1
Cl_15	1	0	0	0	0	0	0	0	0
Cl_17		0	1	1	0	1	1	1	0
Cl_19			0	1	0	0	1	1	0
Cl_30				0	0	0	0	0	0
Cl_37					1	0	0	0	0
Cl_39						0	1	1	0
Cl_MIXED							0	0	0
CP_1								0	1
CP_2									0

**Appendix Table 2: Significance of pair-wise comparisons for Basal area performance by seedlot using Tukey test. A value of 1 represents being significantly different at 95% confidence**

	Clone						Control-pollinated		Open-pollinated
	17	19	30	37	39	Mixed	1	2	1
Cl_15	0	0	0	0	0	0	0	0	0
Cl_17		0	0	0	0	0	1	0	0
Cl_19			0	0	0	0	1	1	0
Cl_30				0	0	0	0	0	0
Cl_37					0	0	0	0	0
Cl_39						0	0	0	0
Cl_MIXED							0	0	0
CP_1								0	1
CP_2									1

**Appendix Table 3: Significance of pair-wise comparisons for height variability by seedlot using Tukey test. A value of 1 represents being significantly different at 95% confidence**

	Clone						Control-pollinated		Open-pollinated
	17	19	30	37	39	Mixed	1	2	1
Cl_15	0	0	0	0	0	0	1	0	1
Cl_17		0	0	0	0	0	1	0	0
Cl_19			0	0	0	0	1	0	1
Cl_30				0	0	0	1	0	1
Cl_37					0	0	1	0	1
Cl_39						0	1	0	1
Cl_MIXED							1	0	1
CP_1								0	0
CP_2									0

**Appendix Table 4: Significance of pair-wise comparisons for DBH variability by seedlot using Tukey test. A value of 1 represents being significantly different at 95% confidence**

	Clone						Control-pollinated		Open pollinated
	17	19	30	37	39	Mixed	1	2	1
Cl_15	0	0	0	0	0	0	0	0	0
Cl_17		0	0	0	0	0	0	0	0
Cl_19			0	0	0	0	0	0	0
Cl_30				0	0	0	1	0	1
Cl_37					0	0	0	0	0
Cl_39						0	0	0	0
Cl_MIXED							0	0	0
CP_1								0	0
CP_2									0

### **Linear models**

Call:  
lm(formula = total\_ht ~ Predicted + Seedlot + Rep, data = LIDAR)

Residuals:

Min	1Q	Median	3Q	Max
-0.89639	-0.14615	0.02009	0.16647	0.54919

Coefficients: (1 not defined because of singularities)

	Estimate	std. Error	t value	Pr(> t )	
(Intercept)	5.21618	1.26956	4.109	0.000198	***
Predicted	1.49798	0.24697	6.066	4.20e-07	***
seedlotCl_17	0.90180	0.20548	4.389	8.42e-05	***
seedlotCl_19	0.32115	0.16324	1.967	0.056288	.
seedlotCl_30	-0.30129	0.17894	-1.684	0.100228	
seedlotCl_37	-0.03609	0.16407	-0.220	0.827047	
seedlotCl_39	0.03506	0.16693	0.210	0.834752	
seedlotCl_MIXED	0.10445	0.16272	0.642	0.524680	
seedlotCP_1	0.91196	0.20592	4.429	7.45e-05	***
seedlotCP_2	-0.10779	0.22569	-0.478	0.635596	
seedlotOP_1	NA	NA	NA	NA	
Rep	-0.02095	0.02970	-0.705	0.484751	

---  
signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.297 on 39 degrees of freedom  
Multiple R-squared: 0.8865, Adjusted R-squared: 0.8574  
F-statistic: 30.46 on 10 and 39 DF, p-value: 2.303e-15

**Appendix Figure 1: Summary of R outputs for whole area LIDAR height vs plot height**

```

Call:
lm(formula = total_ht_c ~ Predicted_c + Seedlot, data = LIDAR)

Residuals:
    Min       1Q   Median       3Q      Max
-3.5197 -0.5588 -0.0152  0.3415  4.1167

Coefficients: (1 not defined because of singularities)
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   107.2302    21.5035   4.987 1.24e-05 ***
Predicted_c    -3.5437     0.7546  -4.696 3.10e-05 ***
SeedlotCl_17    7.7379     1.9115   4.048 0.000230 ***
SeedlotCl_19   -4.5420     0.9832  -4.619 3.95e-05 ***
SeedlotCl_30   -7.1715     1.2729  -5.634 1.54e-06 ***
SeedlotCl_37   -4.5817     0.8607  -5.323 4.20e-06 ***
SeedlotCl_39   -7.1131     1.3926  -5.108 8.40e-06 ***
SeedlotCl_MIXED -1.2861     0.7326  -1.756 0.086821 .
SeedlotCP_1    16.8489     3.1573   5.336 4.03e-06 ***
SeedlotCP_2     3.9810     1.1067   3.597 0.000875 ***
SeedlotOP_1           NA          NA      NA      NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.336 on 40 degrees of freedom
Multiple R-squared:  0.6512,    Adjusted R-squared:  0.5727
F-statistic: 8.296 on 9 and 40 DF,  p-value: 7.737e-07

```

Appendix Figure 2: Summary of R outputs for whole area LIDAR height CV vs plot height CV

Appendix Figure 2:

```

Call:
lm(formula = plot_total_ht ~ MEAN + Seedlot, data = lidard)

Residuals:
    Min       1Q   Median       3Q      Max
-0.28323 -0.08247 -0.00929  0.08548  0.35779

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   7.80482    0.57371  13.604 < 2e-16 ***
MEAN           0.98449    0.10045   9.801 4.51e-12 ***
SeedlotCl_17    1.08997    0.10157  10.731 3.34e-13 ***
SeedlotCl_19    0.28200    0.11135   2.532 0.01546 *
SeedlotCl_30   -0.56906    0.12743  -4.466 6.65e-05 ***
SeedlotCl_37   -0.11658    0.11961  -0.975 0.33574
SeedlotCl_39   -0.07245    0.12357  -0.586 0.56102
SeedlotCl_MIXED 0.06871    0.11403   0.603 0.55025
SeedlotCP_1     0.41048    0.13251   3.098 0.00361 **
SeedlotCP_2    -0.52781    0.15127  -3.489 0.00122 **
SeedlotOP_1    -0.43130    0.12464  -3.460 0.00132 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1606 on 39 degrees of freedom
Multiple R-squared:  0.9668,    Adjusted R-squared:  0.9583
F-statistic: 113.6 on 10 and 39 DF,  p-value: < 2.2e-16

```

Appendix Figure 3: Summary of R outputs for plot area LIDAR height vs plot height

```
Call:
lm(formula = plot_total_ht_cv ~ Cov + Seedlot, data = lidard)
```

```
Residuals:
    Min       1Q   Median       3Q      Max
-2.7888 -0.5742  0.0200  0.4545  4.0338
```

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   -2.66422     3.46783   -0.768 0.446955
Cov             0.26178     0.12881    2.032 0.048971 *
SeedlotCl_17    0.05396     1.05877    0.051 0.959616
SeedlotCl_19    0.33812     0.81914    0.413 0.682035
SeedlotCl_30   -0.28832     0.81394   -0.354 0.725074
SeedlotCl_37   -0.75470     0.82582   -0.914 0.366395
SeedlotCl_39    0.29327     0.81692    0.359 0.721537
SeedlotCl_MIXED 0.30576     0.82324    0.371 0.712343
SeedlotCP_1     3.90050     0.85174    4.579 4.67e-05 ***
SeedlotCP_2     1.71850     0.83184    2.066 0.045527 *
SeedlotOP_1     3.56324     0.83806    4.252 0.000128 ***
```

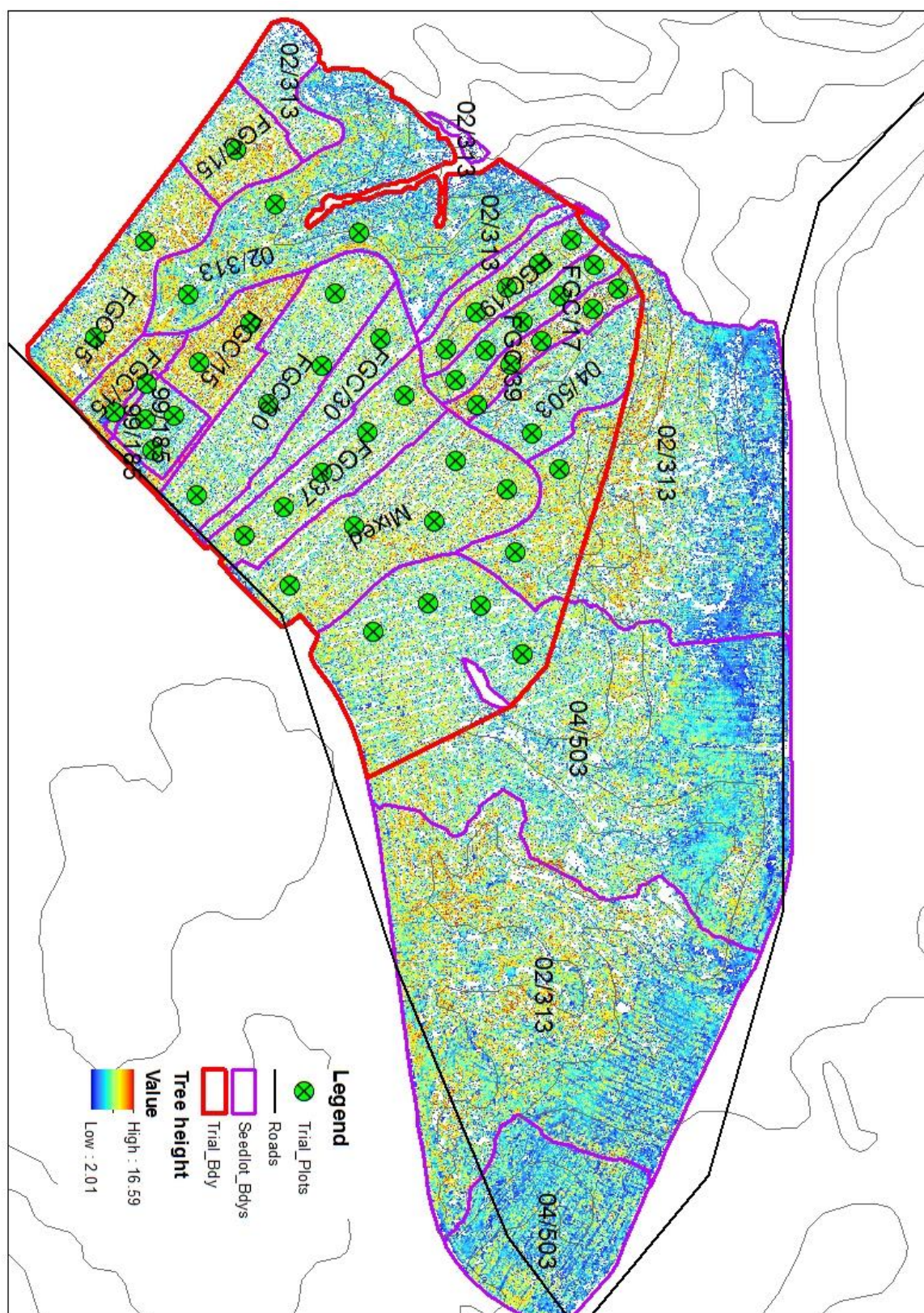
```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 1.287 on 39 degrees of freedom
Multiple R-squared:  0.6846,    Adjusted R-squared:  0.6037
F-statistic: 8.464 on 10 and 39 DF,  p-value: 3.959e-07
```

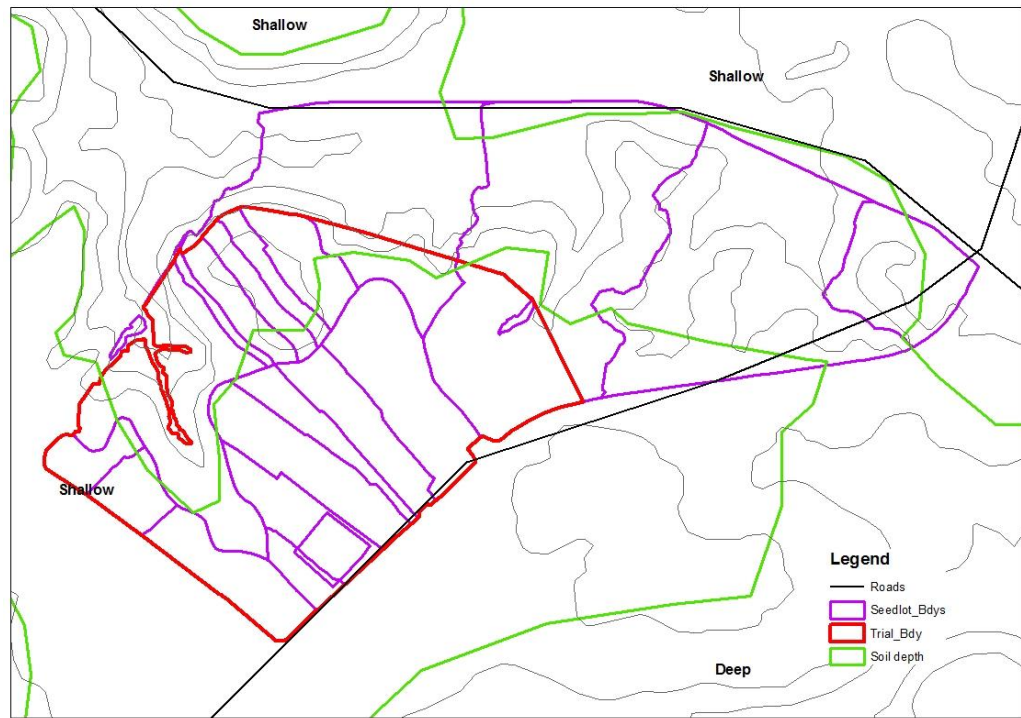
**Appendix Figure 4: Summary of R outputs for plot area LIDAR height CV vs plot height CV**



## Trial Maps

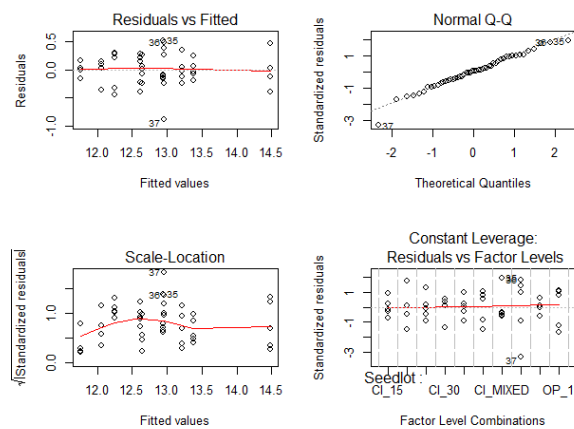


Appendix Figure 5: Trial area map with seedlot boundaries and LIDAR tree height.

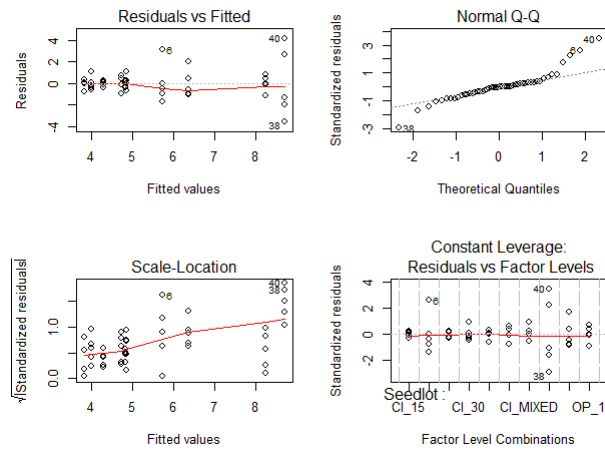


Appendix Figure 6: Soil depth across trial area (LINZ, 2016).

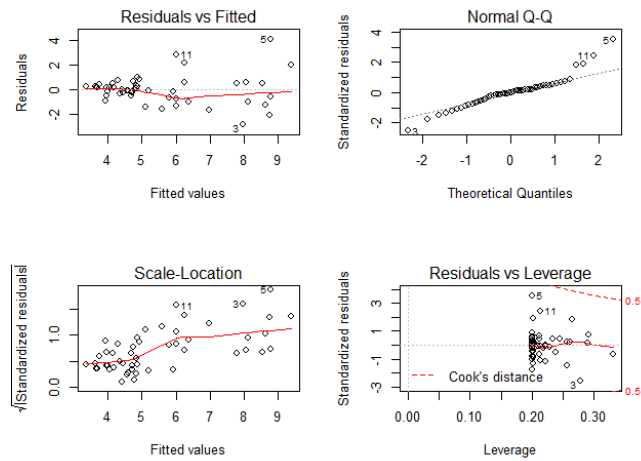
### Residual analysis of linear models



Appendix Figure 5: Residual analysis of whole area LIDAR height vs plot heights



**Appendix Figure 6: Residual analysis of whole area LIDAR height CV vs plot CV**



**Appendix Figure 7: Residual analysis of plot area LIDAR height CV vs plot height CV**